UNCLASSIFIED

Copy

IDA DOCUMENT D-1798

REVIEW OF LITERATURE ON ENVIRONMENTALLY CONSCIOUS DESIGN

J. C. Rigby

December 1995

19960508 173

Prepared for
The Office of the Deputy Under Secretary of Defense
for Environmental Security, DUSD (ES)
and
The Army Environmental Policy Institute (AEPI)

Approved for public release, unlimited distribution: 12 April 1996.

DTIC QUALITY INSPECTED 3

IDA

INSTITUTE FOR DEFENSE ANALYSES
1801 N. Beauregard Street, Alexandria, Virginia 22311-1772

UNCLASSIFIED

IDA Log No. H 95-47481

DEFINITIONS

IDA publishes the following documents to report the results of its work.

Reports

Reports are the most authoritative and most carefully considered products IDA publishes. They normally embody results of major projects which (a) have a direct bearing on decisions affecting major programs, (b) address issues of significant concern to the Executive Branch, the Congress and/or the public, or (c) address issues that have significant economic implications. IDA Reports are reviewed by outside panels of experts to ensure their high quality and relevance to the problems studied, and they are released by the President of IDA.

Group Reports

Group Reports record the findings and results of IDA established working groups and panels composed of senior individuals addressing major issues which otherwise would be the subject of an IDA Report. IDA Group Reports are reviewed by the senior individuals responsible for the project and others as selected by IDA to ensure their high quality and relevance to the problems studied, and are released by the President of IDA.

Papers

Papers, also authoritative and carefully considered products of IDA, address studies that are narrower in scope than those covered in Reports. IDA Papers are reviewed to ensure that they meet the high standards expected of refereed papers in professional journals or formal Agency reports.

Documents

IDA Documents are used for the convenience of the sponsors or the analysts (a) to record substantive work done in quick reaction studies, (b) to record the proceedings of conferences and meetings, (c) to make available preliminary and tentative results of analyses, (d) to record data developed in the course of an investigation, or (e) to forward information that is essentially unanalyzed and unevaluated. The review of IDA Documents is suited to their content and intended use.

The work reported in this document was conducted under contract DASW01 94 C 0054 for the Department of Defense. The publication of this IDA document does not indicate endorsement by the Department of Defense, nor should the contents be construed as reflecting the official position of that Agency.

UNCLASSIFIED

IDA DOCUMENT D-1798

REVIEW OF LITERATURE ON ENVIRONMENTALLY CONSCIOUS DESIGN

J. C. Rigby

December 1995

Approved for public release, unlimited distribution: 12 April 1996.

INSTITUTE FOR DEFENSE ANALYSES

Contract DASW01 94 C 0054

Task T-AM1-1290

UNCLASSIFIED

PREFACE

This document examines the literature on environmentally conscious design in support of a task initiated by the Office of the Deputy Under Secretary of Defense for Environmental Security [DUSD(ES)] and the Army Environmental Policy Institute (AEPI). Because of its general applicability to systems development and acquisition and its utility as an information resource, it is being published as a separate document that may be used alone or in conjunction with other documents published as part of that task. Those documents, prepared by the Institute for Defense Analyses (IDA) under Contract DASW01-94-C-0054, Task Order T-AMI-1290, dated May 1994, include the following:

- *Pollution Prevention: Early Identification of Hazardous Materials Destined for Use by the Army in Systems Acquisition*, dated 31 May 1994.
- *Avoiding Environmentally Hazardous Materials in the Army Acquisition Process,* IDA Paper P-3081, dated April., 1995.
- *Reducing the Life Cycle Costs of Future Army Materiel Acquisitions by Good Environmental Design*, IDA Document D-1824. Draft, dated February 1996. Report in progress.

We believe this annotated bibliography can serve as a guide to the state of the art in the field of environmentally conscious design not only for this task but also for the Army and DoD systems development and acquisition communities in general. It identifies and summarizes recent publications and conference proceedings in the emerging disciplines of industrial ecology and design for the environment, as well as articles and books addressing life cycle assessment and related tools for environmentally conscious manufacturing. The literature review includes the fields of electrical engineering and mechanical engineering as well as systems engineering and environmental science. It provides a guide to essential reading on issues of environmentally conscious design across a variety of application areas including, but not limited to, aeronautical, automotive, and information systems. It can provide a resource to Program Executive Officers, Project Managers, and their staffs as well as developers in the Research Development and Engineering Centers (RDECs) as they work to address issues of pollution prevention in future Army and DoD systems.

Ms. Joyce C. Rigby researched the literature and wrote the abstracts included in this document. The material was reviewed by Dr. Joel E. Tumarkin, project leader of the task, Dr. Frederick R. Riddell, and Dr. J. Scott Hauger. Their comments and suggestions are gratefully acknowledged.

CONTENTS

LIST OF FIGURES

(This page is intentionally blank.)

REVIEW OF LITERATURE ON ENVIRONMENTALLY CONSCIOUS DESIGN

This report examines the literature on environmentally conscious design to determine what tools/methodologies currently exist, or are under development, that could assist the Army in its goal to consider environmental impacts of a product during the design stage of that product.

Many terms pertaining to environmentally conscious design are often used interchangeably. Section A is organized by these terms to better present the differences. Industrial Ecology is the broadest term that takes a systems view of the environment and the industrial sector. Environmentally Conscious Design/Manufacturing is a term that represents industry's commitment to the environment. Other terms, e.g., design for environment and life cycle assessment, are specific methodologies to achieve this positive commitment. Figure 1 presents an overview of the topics discussed.

The literature examined in this document was obtained through the Virginia Polytechic Institute (VPI) Library System and includes items in Virginia Tech's Newman Library as well as items ordered through interlibrary loan. Section C presents a list of referenced documents that were not included in this review but that could serve as a beginning for further research, if desired.

A. OVERVIEW OF LITERATURE

1. Industrial Ecology

Industrial ecology is currently emerging as a science for integrating technological and environmental systems. It considers the natural environment as a model for the solution of environmental problems. Ernest Lowe (1993) cites recent cooperative initiatives between companies so that one's waste becomes another's raw material or energy resource. The examples "suggest the power of moving beyond individual company or plant boundaries to seek improvements in performance of larger systems." Graedel and Allenby (1995) define industrial ecology in the following paragraph:

> Industrial ecology is the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal.

O'Dea and Freeman (1995) support this concept by demonstrating how Integrated Logistics Support can be used to design an eco-industrial park, which is a park where the companies work together to minimize environmental impacts, for example, by using each others' outputs as their raw material or energy resource.

2. Design for Environment

The term, design for environment (DFE) is used in differing ways in the literature. Frequently it is used to designate an overall viewpoint that encompasses all of the practices in designing a product or process with the environment in mind. I have chosen to employ the term more literally, that is, as a concurrent engineering methodology, in accordance with Graedel and Allenby's new book, *Industrial Ecology,* (1995).

Graedel and Allenby differentiate between product design and process design. Industrial ecology involves both processes and products. However, the designers of each are usually different. Processes can be embedded in an industry and take a long time to replace with another process. DFE practices are directly a part of product design, not process design. However, DFE may affect the manufacturing process, if, for example, a plastic is chosen over aluminum as a component part, thus changing the process. DFE is a concurrent engineering practice. Concurrent engineering practices use a design system known as "Design for X," or DFX, which is implemented early in the design process of a product. "X" stands for a desirable product characteristic such as, quality (Q), recyclability (R), manufacturability (M), or disassembly (D).

DFE methodologies are being developed in response to attention focused on the environmental impacts of a product. The current state of the art is still young and usually applied to somewhat simple consumable products. More complex systems, such as automobiles, airplanes, electronic products, and weapons systems present a greater challenge.

3. Life Cycle Assessment

At the forefront of the current state of the art of industrial ecology tools is life cycle assessment (LCA). LCA is a continually evolving methodology. Some authors refer to LCA as life cycle analysis. This term is interchangeable with life cycle assessment.

Life Cycle Assessment is a tool that can be used in both product and process design. LCA is the most discussed concept in the literature. An LCA seeks to include all the environmental impacts of a product in evaluating the desirability of choosing that product or the components for the product. In this "cradle to grave" approach, everything is considered from raw material acquisition and refinement, manufacturing processes, transportation and energy usage, consumer use of the product, and disposal or recyclability of the product. LCA can also be used in a more limited scope to answer specific questions or concerns. For example, an LCA comparison of two cleaning processes for a product could be limited to the inputs and outputs of the cleaning procedure, since other stages of the life cycle would remain the same and therefore have no relevance to the LCA. Most of the LCAs that have been performed to date are in actuality only the life cycle inventory step of the LCA (see below).

The Society for Environmental Toxicology and Chemistry (SETAC) has been instrumental in defining LCA. SETAC has held a series of workshops whose goals have been to further develop the LCA methodology. The results of these workshops are published in four volumes, Consoli, et al. (1993), Fava, Consoli, et al. (1993), Fava, Denison, et al. (1991), and Fava, Jensen, et al. (1994). The following definition of LCA comes from Fava, Denison, et al. (1991):

> The life-cycle assessment is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment, to assess the impact of those energy and materials uses and releases on the environment, and to evaluate and implement opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process, or activity, encompassing extraction and processing of raw materials, manufacturing, transportation and distribution, use/re-use/maintenance, recycling, and final disposal.

According to the SETAC workshops, LCA consists of four components: goal definition and scoping, inventory analysis, impact analysis, and improvements analysis.

Goal definition identifies the overall purpose of the LCA. Scoping identifies the boundaries, assumptions, and limitations of the LCA. If the goal of an LCA is to improve

an existing product, an approach might be to analyze each component according to several environmental criteria, and then choose improvements accordingly. If the goal of the LCA is to compare an existing design with an alternative design, more in-depth analysis is needed and the scope of the LCA might have to be broad enough to include the "cradle to grave" analysis.

Inventory analysis provides information on the inputs and outputs of a system. Gathering information for an inventory analysis is a very detailed and labor intensive task. Some information may be proprietary and difficult to come by, e.g., supplier information on a patented process. Other data may be available through widely published industry estimates, such as energy usages. When a similar product exists (to the proposed product), it may be used as a model for the proposed product. The need for computer-generated databases will increase as a company generates this information so that it may be reused as appropriate.

Impact analysis seeks to understand the environmental effects of a product by assigning relative values to the inventory data according to their impact on the environment.

Improvements analysis uses the insights of the inventory and impact analyses steps and identifies and evaluates opportunities for improving the environmental impact of a product or process. Warren and Weitz further develop LCA by adding cost components, as does Cohan and Gess.

4. Other Tools

Additional approaches to environmentally conscious design include the development and use of computer tools such as expert systems (Benda, et al.), Green Design Advisor (Wixom), and a life-cycle cost integration model (Warren and Weitz). Other approaches include integrated life-cycle management (Cohan and Gess, and Fiksel), a "systematic methodology" (Chen, et al.), application of total quality management (TQM) practices (McGee and Bhushan, and Thompson and Rauck), integrated logistics eco-support (O'Dea and Freeman), front-end environmental analysis (Coogan), environmentally oriented milestone questions (Keldman and Olesen), life cycle design multicriteria matrix (Keoleian, et al.), pollution prevention (Flynn, Overby, Salomon, and U. S. Army), recycling and remanufacturing (Chen, et al., Hundal, Kuuva and Airila, Steinhilper, and U. S. Army), a pre-life-cycle assessment tool (Tolle, et al.), and a life cycle cost assessment model (Warren and Weitz). Additional approaches mentioned by

Fiksel include quality metrics, environmental management of materials, risk analysis, life-cycle costing, and system-oriented design.

Many companies have begun to implement their environmentally conscious approach to design and manufacturing. Pratt & Whitney has developed a Consolidated Pollution Prevention Team whose mission is to establish a pollution prevention strategy (Flynn). The Computer Products Division at Hewlett-Packard has developed a set of metrics for the life cycle assessment process to be used when improving a design (Korpalski). Hewlett-Packard Company has also developed performance expectations for their suppliers that include environmental factors (Maxie). AT&T has used life cycle design as a framework for a demonstration project for a business phone (Keoleian, et al.). Pitney Bowes has developed a framework for implementing a Design for Environmental Quality (DFEQ) program (Ryberg). Salomon describes pollution prevention paradigms at three DoD contractors: Lockheed Aeronautical Systems Company, Lockheed Fort Worth Company, and McDonnell Douglas Aerospace - East. Hughes Radar Systems has developed the Green Notes Environmental Rating and Measurement system (Schutzenberger). Digital Equipment Corporation has developed a Pre-LCA tool that is a streamlined approach to LCA (Tolle, et al.). The J.M. Huber Corporation has developed a management and measurement tool called the Huber Environmental Performance Index (HEPI), which allows Huber to track environmental progress across Huber's 12 different divisions (Wells and Calkins).

Nonmanufacturing, consulting firms that have published documents included in this literature review include Batelle, Decision Focus, Inc., Center for Economics Research at Research Triangle Institute, and Abt Associates Inc.

Universities represented in this literature review include Carnegie Mellon University, University of Connecticut, Michigan State University, Ohio State University, Massachusetts Institute of Technology, University of Vermont, Helsinki University of Technology, The Danish Technical University, Fraunhofer-Institut Für Produktionstechnik, and the University of Illinois.

Figure 1. Cross-Reference of Topics and Authors

Authors	Overview of Issues	International Issues	Industrial Ecology	DFE	LCA	LCD	Management Issues	Computer Tools	Cost Analysis	Corporation Specific	Multicriteria Rating	Material Selection	Supplier Performance	Product Development	Recycling/Recyclability	Remanufacturing	Front-End Analysis	Pollution Prevention
Allenby (1993)	X																	
Allenby (1993, Spring)	X			X														
Allenby (1994)				X	X													
Ashley (1993)				X														
Benda, et al. (1993)					X			ES										
Billatos, et al. (1994)				X														
Cascio (1993)		X																
Chen, et al. (1993)								X	X						X			
Cohan & Gess (1994)					X		X		X									
Consoli, et al. (1993)					X				ILCM									
Coogan (1993)																	X	
Fava (1993)					X													
Fava, Consoli, et al. (1993)					X													
Fava, Denison, et al. (1991)					X													
Fava, Jensen, et al. (1994)					X													
Field, et al. (1993)		X			X													
Fiksel (1993)				X					ILCM									
Fiksel (1993/94, Winter)				X	X													
Fiksel & Wapman (1994)				X	X				X									
Fouhy (1993)					X													
Flynn (1994)					X													X
Glantschnig (1993)	X																	
Gosh (1992)		X																
Graedel (1994)					X													
Graedel & Allenby (1995)	X		X	X	X						X	X		X	X			
Hermann (1994)		X																
Hundal (1994)		X		X											X	X		
Keldman & Olesen (1994)										X				X				
Keoleian, et al. (1994)						X				X								
Keoleian & Menerey (1993)						X			X					X				
Korpalski (1994)					X					X								
Kuuva & Airila (1994)				X											X			
Legarth, et al. (1994)					X													
Lifsei (1991)					X													
Lowe (1993)			X	X			X			X								
Maxie (1994)													X					

Figure 1. (Continued)

Authors	Overview of Issues	International Issues	Industrial Ecology	DFE	LCA	LCD	Management Issues	Computer Tools	Cost Analysis	Corporation Specific	Multicriteria Rating	Material Selection	Supplier Performance	Product Development	Recycling/Recyclability	Remanufacturing	Front-End Analysis	Pollution Prevention
McGee & Bhushan (1993)							TQM											
O'Dea & Freeman (1995)			X				ILS											
Overby (1991)							X											X
Parker & Boyd (1993)				X														
Rethmeyer (1993)					X			X										
Rhodes (1993)					X													
Ryberg (1993)				X						X								
Salomon (1994)							X											X
Schutzenberger (1994)										X	X			X				
Steinhilper (1994)		X													X	X		
Sullivan & Young (1995)					X													
Thompson & Rauck (1993)							TQM											X
Thurston (1994)					X						X							
Tolle, et al. (1994)					X					P-LCA	X							
U.S. Army Acquisition Pollution Prev. (1994)		X								X		X	X	X	X			X
U.S. EPA, Risk Reduction Engineering Lab (1992)				X														
Vignon & Curran (1993)					X													
Vignon, et al. (1993)					X													
Warren & Weitz (1994)					X			LCM	LCCA									
Wells & Calkins (1994)					X		HEPI			X	X							
Wenzel, et al. (1994)		X	X		X									X				
Wixom (1994)								GDA										
Young & Vanderburg (1994)					X							X						

B. LITERATURE ABSTRACTS

Allenby, Braden R., "An International Design for Environmental Infrastructure: Concept and Implementation," *Proceedings of the 1993 IEEE International Symposium on Electronics and the Environment*. Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1993, pp. 49-55.

This paper presents an overview of the complexity of the issues involved in designing for the environment. The author presents his argument for the need for an international environmental infrastructure developed by governments in cooperation with society and industry. This infrastructure would include the following tools: more comprehensive data sets, socially accepted risk prioritization schemes and methodologies, decision rules for value and ethical judgments, and appropriate modification of existing regulatory and statutory requirements.

Allenby, Braden. "Supporting Environmental Quality: Developing an Infrastructure for Design," *Total Quality Environmental Management*, Spring 1993, pp. 303-308.

Dr. Allenby suggests that a national, and preferably an international, infrastructure be established for design for the environment (DFE). This infrastructure should address comprehensive data sets, socially acceptable risk prioritization schemes, and decision rules for value and ethical judgments. It is an appropriate task of government to create such DFE infrastructure tools. The author gives three supporting reasons for this need:

1. Companies that manufacture complex products do not usually extract the raw materials incorporated in their products, not do they usually deal with the post consumer disposal of their products.
2. Analysis of the environmental data requires value judgments that may cross geographical boundaries or timeline effects in the distribution of the risks involved. The author gives the following example for this issue:

   An analysis of the desirability of substituting indium or bismuth alloys for lead solder in printed wiring board assemblies leads directly to difficult risk distribution questions. Environmental impacts of increased use of bismuth and indium would fall on localities where mining and processing occurred, whereas benefits would accrue primarily to localities near landfills or incinerators where the electronic items containing alloys would be deposited... There is very little indium in the world; is it an appropriate use of this limited stock to consume it in electronics applications now, when adequate substitutes exist, thereby making it essentially unrecoverable for future generations?

3. The third reason deals with the legal infrastructure already in place.

   Obviously, existing environmental laws that presuppose linear manufacturing activities, and thus penalize the development of materials cycling systems are a major issue. The Resource Conservation and Recovery Act in the United States is one example. Another, less obvious, example is antitrust law in general, with its restrictions on vertical integration, and joint action among competitors regarding, for example, technologies and standard-setting activity (necessary for life-cycle control of material flows). Similarly, consumer protection laws discriminating against refurbished goods in commerce, and government procurement laws and regulations prohibiting governments from purchasing such items, obviously

reduce incentives to recycle and refurbish components, subassemblies, and products.

Allenby, Braden R., "Integrating Environment and Technology: Design for Environment." In Braden R. Allenby and Deanna J. Richards (Eds.), *The Greening of Industrial Ecosystems*. Washington, DC: National Academy Press, 1994.

This article addresses the need for a Design for Environment (DFE) approach to be implemented into industrial practices. The author states five principles on which to base development of methodologies for integrating technological and environmental systems. They are:

1. Methodologies should be comprehensive and systems-based.
2. Methodologies should be multidisciplinary, including technical, legal, economic, political, and cultural dimensions to the extent possible.
3. Mitigation of environmental perturbations can only be achieved by focusing on technology, and developing policies and practices that encourage the evolution of environmentally preferable process and product technologies.
4. Economic actors, including private firms, must internalize environmental considerations and constraints to the extent possible, given existing exogenous constraints on firm behavior (e.g., laws such as the antitrust statutes or the prices of inputs and competitive products).
5. Policies and regulations must reflect the need for experimentation and research as different paths and methodologies are tried.

DFE can be used to evaluate large, comprehensive projects across all design functions or specific products, processes or inputs. DFE activities usually involve an analysis of options. Basic steps include scoping, data gathering, and data translation. According to Allenby, "no firm has yet implemented a comprehensive DFE system, and, indeed, fully implementing DFE practices will in all likelihood require that most firms develop new competencies, organizations, and information systems."

Life cycle analysis (LCA) is described as the concept that all environmental impacts of an item, from inputs to disposal, should be considered in evaluating the "environmental preferability of the product."

The author gives an example of a DFE Information System methodology used at AT&T and its application in the examination of alternatives to lead solder currently used in printed wiring boards.

Ashley, Steven "Designing for the Environment," *Mechanical Engineering*, March 1993, pp. 52-55.

The author introduces the concept of design for the environment and gives examples of its current state of the art with references to the activities by the National Academy of Engineering's Technology and Environment Program, the Congressional Office of Technology Assessment, the National Center or Manufacturing Sciences, and the Environmental Protection Agency. Also mentioned are environmentally conscious programs at AT&T, Whirlpool, IBM, Xerox, Digital Equipment, GE Plastics, Ford Motor Co., and Volvo.

Benda, James, Narayan, Ramani, and Sticklen, Jon. "Use of Expert Systems for Life Cycle Analysis," *Automobile Life Cycle Tools and Recycling Technologies, SAE Special Publications* , Warrendale, PA: SAE, 1993, pp. 53-57.

The authors state some common problems with life cycle analysis, namely, data limitation, assumptions, lack of a standard, cost, lack of a common currency, boundary definitions, weighting factors, and data aggregation. The authors propose the development and use of expert systems to solve these problems. They propose using the Hierarchical Classification technique which is a task specific architecture approach.

Billatos, Samir B., and Nevrekar, Vishnu V. "Challenges and Practical Solutions To Designing for the Environment," *Design for Manufacturability 1994: An Environment for Improving Design and Designing to Improve Our Environment.* New York: The American Society of Mechanical Engineers, 1994, pp. 49-64.

The authors introduce Design for the Environment (DFE) and compare it with other design tools such as, Just in Time methods (JIT), Design for Disassembly (DFD) and Design for Manufacture and Assembly (DFMA). The authors introduce 13 DFE Guidelines, as follows:

1. Keep the design simple by using as few materials as possible. Also, incorporate as many functions as possible into any single part without compromising function. Avoid secondary finishes, toxic materials and heavy metals which can contaminate material.
2. Find multiple or secondary uses for a product. Disposal will be less of a problem if a product has more "intrinsic value". As an example, a container protecting a product could also store the accessories that come with it.
3. To ensure easier recycling, use materials that match each other closely or the same material. Look for ways to use recycled materials as starting compounds for a product.
4. Modular design should be preferred whenever possible. This helps in maintenance and repair—a "black box" concept.
5. Design for long product life and become more service-oriented. If a manufacturer upgrades its product as technologies improve, a more loyal customer base is assured.
6. Ensure tracking mechanisms are available on a "cradle-to-grave" basis. Ensure up-to-date databases are available. Ensure parts are marked with logos to aid in recycling efforts.
7. Examine those components in a design that may be reused upon failure or disassembly. This would reduce the need to recycle or dispose.
8. Establish a network of producers and suppliers to form the beginnings of the "industrial ecosystem" and facilitate DFE efforts.
9. Look to reduce waste by-product streams in manufacturing processes. Seek out non-hazardous solvents and cleaning materials. Reduce energy consumption by eliminating unnecessary manufacturing steps.
10. Ensure a product "buy back" infrastructure is in place and well advertised to suppliers, producers and consumers.

11. Pay close attention to recyclability and reuse of packaging, shipping and other peripheral requirements. Design reusable shipping vehicles.
12. Whenever possible, attempt to incorporate a concurrent engineering philosophy: JIT, DFMA, DFD to aid the overall DFE effort. Design for total ease of assembly, separation, handling, and cleaning.
13. Apply tight tolerance design principles to reduce the use of fasteners and keep the separation process simple.

Cascio, Joe. "International Environmental Standardization," *Proceedings of the 1993 IEEE International Symposium on Electronics and the Environment*, Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc. 1993, pp. 157-159.

The author presents justification for developing international environmental standards.

Chen, Rosy W., Navin-Chandra, D., Kurfess, T., & Prinz, F. "A Systematic Methodology of Material Selection with Environmental Considerations," *Proceedings of the 1994 IEEE International Symposium on Electronics and the Environment*, Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1994, pp. 252-257.

The authors present a methodology that incorporates environmental considerations into the material selection process. This methodology is based on minimizing cost while meeting environmental, functional, geometric and material property requirements. The methodology considers the following environmental factors in material selection: energy consumption, energy emissions, and solid waste disposal. The methodology evaluates materials selected based on a total cost that is a function of "performance, geometry and material properties as well as material, manufacturing, and environment costs." The authors illustrate this methodology by applying it to the housing of an electronic device.

Chen, Rosy W., Navin-Chandra, D., & Prinz, F. B. "Product Design for Recyclability: A Cost Benefit Analysis Model and Its Application," *Proceedings of the 1993 IEEE International Symposium on Electronics and the Environment*, Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1993, pp. 178-183.

This paper presents a computer-based cost benefit analysis model to be used as a tool when designing for recyclability. The authors also present the following information as a compilation of their experiences, knowledge, communications with other professionals, and published resources:

Suggested rules for material selection:

- Use recyclable materials if engineering requirements are satisfied.
- Use compatible materials for adjacent parts and subassemblies.
- Use recycle materials if they meet the engineering requirements.
- Avoid using toxic materials.
- Minimize material variety if possible.
- Avoid secondary finishes such as painting, coating, etc.

Suggested rules for ease of disassembly:

- Choose joints that are easy to disassemble if the material is not recyclable or compatible.
- Simplify and standardize component fits and interfaces.
- Identify separation points.
- Use water-soluble adhesives where possible.
- Label materials to ease identification and separation.
- Layout plastic parts close to the top level of the disassembly path.
- Design for ease of handling and cleaning of components.
- Choose easy separating joints for parts which have reuse value.
- Provide "easy to see" access for disassembly.
- Use rust proof joints if parts to be exposed to harsh environments.
- Use the same size of joints (same system) for adjacent parts.
- Provide access for hand tool and power tool operation.

Cohan, David, and Gess, David. "Integrated Life-Cycle Management," *Proceedings of the 1994 IEEE International Symposium on Electronics and the Environment,* Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1994, pp. 149-154.

Integrated life-cycle management (ILCM) combines the life-cycle approach with cost analysis. "Unlike other life-cycle approaches, ILCM explicitly focuses on the firm's business decisions which, together with the firm's goals, guide the scope of the implementation." This scope might be broad to include the total life cycle or it might be narrow to include only those stages of the life cycle that are controlled by the firm. Or, it could be driven by customer needs, and focus on only that stage of the life cycle. The paper describes several potential implementations of ILCM that could be tailored specifically to the company's goals. The paper then describes specific examples of ILCM applications.

Consoli, Allen, Boustead, Fava, Franklin, Jensen, de Oude, Parrish, Perriman, Postlethwaite, Quay, Séquin, and Vigon (Eds.). *Guidelines for Life-Cycle Assessment: A 'Code of Practice,'* Pensacola, FL: Society of Environmental Toxicology and Chemistry (SETAC), 1993.

This book is a cooperative effort by European and North American organizations of the Society of Environmental Toxicology and Chemistry in response to the need for guidance in Life-Cycle Assessment (LCA). A series of workshops were held with this international community that reflect consensus on methods for LCA. This book represents their effort in establishing guidelines for LCA and presents general principles and a framework for "the conduct, review, presentation, and use of LCA findings."

The authors present the following definition for Life-Cycle Assessment:

> Life-Cycle Assessment is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and material uses and releases to the environment; and to identify and evaluate opportunities to affect environment improvements. The assessment includes the entire life-cycle of the product, process, or activity, encompassing extracting and processing raw materials; manufacturing; transportation and distribution;

use, re-use, maintenance; recycling, and final disposal (Fava, Denison, et al.). (p.5)

The following is an outline of the steps and sub steps involved in a Life-Cycle Assessment:

1. Goal Definition and Scoping
    - 1.1. Purpose
    - 1.2. Scope
    - 1.3. Functional Unit
    - 1.4. Data-Quality Assessment
2. Inventory Analysis
    - 2.1. Defining Systems and System Boundaries
    - 2.2. Process Flow-Charts
    - 2.3. Data
        - 2.3.1. Data Collection
        - 2.3.2. Calculation Procedures
        - 2.3.3. Inventory Tables
        - 2.3.4. Data Variability, Uncertainties, and Sensitivity Analysis
        - 2.3.5. Deliberate Omissions
    - 2.4. Allocation Procedures
        - 2.4.1. Coproducts
        - 2.4.2. Waste Treatment Processes
        - 2.4.3. Recycling
    - 2.5. Treatment of Energy
3. Impact Assessment
    - 3.1. Classification
    - 3.2. Characterization
    - 3.3. Valuation
4. Improvement Assessment
5. Analyses and Interpretation of Results

Each of these steps are discussed in the book. A chapter is devoted to Data Quality which discusses primary data ("information directly obtained from individual companies") and secondary data (information "obtained from published sources in the form of data bases, industry or government publications, journals or books"). Other key points in the book include:

> LCA addresses environmental impacts of the system under study in the areas of ecological health, human health, and resource depletion. It does not address economic considerations or social effects. (p. 5)
>
> It is generally agreed that only full "cradle-to-grave" evaluations should be described as LCAs. However, much useful information may be derived from studies whose boundaries are narrower than "cradle-to-grave" or for which a full impact assessment has not been conducted, such as Life-Cycle Inventories (LCIs). (p. 37)

> For LCA studies directed toward public audiences, an interactive peer review process at various stages of the LCA can ensure that the study is credible. (p. 50)

The book goes on to give guidelines for the peer review process and also examines further research needs.

Coogan, Charles O. "Front-End Environmental Analysis," *Proceedings of the 1993 IEEE International Symposium on Electronics and the Environment,* Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1993, pp. 144-150.

The author describes how the conventional front end analysis, normally applied to cost of ownership and system utility issues, can be adapted for environmental concerns. Step one is to describe the system. Step two is operational analysis, which includes defining the consumption of fuels or other materials in the operation of the system. Step three is maintenance analysis which describes what is needed to maintain the system. Step four is environmental analysis which describes the environmental impacts of the system. Step five is sensitivity analysis, where variables are varied to determine their impacts on the system and to identify which parameters have the greatest impact. Step six is critical parameter analysis, which identifies actions that can be taken to minimize adverse environmental impacts.

Fava, James A. "Life Cycle Thinking: Application to Product Design," *Proceedings of the 1993 IEEE International Symposium on Electronics and the Environment,* Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1993, pp. 69-73.

The author defines life cycle assessment (LCA) as "a design discipline used to minimize the environmental impacts of products/materials, processes/industrial systems, or activities/services." The author references programs similar to LCA, presents a description on how to start the process of LCA, and references examples of the application of life cycle thinking on product evaluation, design and development.

Fava, Consoli, Denison, Dickson, Mohin, and Vigon (Eds.). *A Conceptual Framework for Life-Cycle Impact Assessment,* Pensacola, FL: Society of Environmental Toxicology and Chemistry (SETAC) and SETAC Foundation for Environmental Education, 1993.

This report represents the outcome of a week-long workshop on the role of impact assessment in life-cycle assessments. The participants represented state and federal agencies, universities, industries, public interest groups, and research laboratories. This report presents the objectives and context of the workshop as follows:

> The workshop participants were charged with defining impact assessment in the context of life-cycle assessment. Additionally, they were asked to discuss and to develop a consensus on whether and how existing impact assessment tools could be applied to LCAs. For those areas where consensus could not be reached, the participants were asked to identify research needs to improve the impact assessment component of LCAs.
>
> Although the impact assessment component is still in an early stage of development, a number of existing impact assessment tools were identified that might be applied to LCAs. This workshop report presents a general conceptual framework for impact assessment from which a technical

framework and specific methods and procedures can be developed. (p. xxiv)

Major findings of the workshop included the following:

- Reaffirmation of the three component model for LCAs (inventory analysis, impact assessment, and improvement assessment).
- Goal definition and scoping steps should be added to that model to help focus and define the scope of an LCA.
- "LCA is not a linear process but one that incorporates feedback loops and requires interaction among the LCA components."
- Major impact categories were defined as: human health, ecological health, and resource depletion.
- Impact Assessment is composed of three phases: classification, characterization, and valuation, per the following definitions from the report:

  Classification—The process of assignment and initial aggregation of data from inventory studies to relatively homogenous stressor categories (e.g., greenhouse gases or ozone depletion compounds) within the larger impact categories (i.e., human and ecological health, and resource depletion). (p. 16)

  Characterization—The analysis and estimation of the magnitude of impacts on the ecological health, human health, or resource depletion for each of the stressor categories, derived through application of specific impact assessment tools. (p.16)

  Valuation—The assignment of relative values or weights to different impacts and their integration across impact categories to allow decision makers to assimilate and consider the full range of relevant impacts across impact categories. Use of formal valuation methods should make this process explicit and collective, rather than one based on implicit, individual value judgments. (p.16)

- Establishment of cause and effect relationships is not the responsibility of an LCA.
- The stressor (set of conditions that may lead to impacts) concept bridges the gap between the inventory and impact assessment components.
- "Research is needed to determine whether or not methods developed for human health and environmental risk assessments, particularly at the generic or programmatic level, could be adapted to the practice of LCA."
- Tools based on decision theory may have some application in the valuation phase.

Fava, Denison, Jones, Curran, Vigon, Selke, and Barnum (Eds.). *A Technical Framework for Life-Cycle Assessments.*, Pensacola, FL: Society of Environmental Toxicology and Chemistry (SETAC) and SETAC Foundation for Environmental Education, 1991.

This book represents the results of a week-long workshop whose participants represented industry, consultants, governmental organizations, universities, public interest groups, and contract research laboratories.

> The workshop objectives were to clarify definitions and terms associated with life-cycle assessments; to provide a forum for information exchange among researchers from government, industry, academia, and public interest groups; and to agree on a technical framework of key life-cycle assessment components. Additional objectives were to identify research needs to improve life-cycle assessment methods and to develop a strategy for furthering the use of life-cycle assessments in evaluating products, processes and activities. (p. xiii)

The book provides the following definition of life-cycle assessment:

> The life-cycle assessment is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment, to assess the impact of those energy and materials uses and releases on the environment, and to evaluate and implement opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process, or activity, encompassing extraction and processing of raw materials, manufacturing, transportation and distribution, use/re-use/maintenance, recycling, and final disposal. (p. 1)

Life-cycle assessment is composed of three components, defined by the workshop participants as follows:

- *Life-Cycle Inventory*—An objective data-based process of quantifying energy and raw material requirements, air emissions, waterborne effluents, solid waste, and other environmental releases throughout the life cycle of a product, process, or activity.
- *Life-Cycle Impact Analysis*—A technical, quantitative, and/or qualitative process to characterize and assess the effects of the environmental loadings identified in the inventory component. The assessment should address both ecological and human health considerations, as well as such other effects as habitat modification and noise pollution.
- *Life-Cycle Improvement Analysis*—A systematic evaluation of the needs and opportunities to reduce the environmental burden associated with energy and raw materials use and environmental releases throughout the whole life cycle of the product, process, or activity. This analysis may include both quantitative and qualitative measures of improvements, such as changes in product, process, and activity design; raw material use; industrial processing; consumer use; and waste management. (pp. 1-2)

This workshop focused on the inventory component of life-cycle assessment. The workshop participants developed a technical framework for life-cycle inventory. According to this framework, the major life-cycle inventory stages are (1) raw materials acquisition; (2) manufacturing, processing, and formulation; (3) distribution and transportation; (4) use/re-use/maintenance; (5) recycling; and (6) waste management. Each of these stages was addressed in depth.

Three additional topics were addressed as needing more investigation: data summation across environmental releases or categories, peer or public review of data sources and inventory methods, and data presentation. Specific research needs pertaining to database development and inventory methodology refinement for life-

cycle inventory were listed, as well as recommendations for future research in the overall area of life-cycle assessment.

Fava, Jensen, Lindfors, Pomper, De Smet, Warren, and Vigon (Eds.). *Life-Cycle Assessment Data Quality: A Conceptual Framework*. Pensacola, FL: Society of Environmental Toxicology and Chemistry (SETAC) and SETAC Foundation for Environmental Education, 1994.

This report is the result of a week long workshop on quality of data used in life-cycle assessments.

Major findings were achieved in the areas of data quality concepts, data quality assessment, data quality assessment framework, and evaluating data quality.

Data quality is defined as "the degree of confidence in individual input data and in the data set as a whole and ultimately in decisions made by using the data." The reliability of an LCA depends on the quality of the input data. Data quality is also influenced by the analyst's degree of knowledge, the assumptions made, and the calculations used to generate the information from the data. Data quality assessment is " a systematic approach to identifying and applying measurements of the suitability of LCA data to meet the intended purpose."

Data quality goals (DQGs) are "specifications for adequacy of input data for an LCA." The data quality goals process is a data quality assessment technique applicable to LCA. The DQGs process consists of the following three activities:

1. *Identification of decision types* focuses on rational and transparent definition of goals, eligibility of potential data sources, and identification of conceptual models for the overall LCA.
2. *Identification of data uses and needs* concerns the identification of data types, data quality requirements, and DQIs commensurate with the DQGs.
3. *Design of data collection programs* addresses data collection, interpretation and documentation, data use and processing into final results, and assessment relative to goals. (p. xviii)

The report gives a graphical representation of the conceptual framework for assessing LCA data quality. The following text describes this framework:

> The process for applying data quality concepts to LCA begins with the establishment of preliminary DQGs for the overall study, and perhaps for certain life-cycle stages and data categories, during the initial goal definition and scoping component. These preliminary DQGs are based on the purpose and scope of the study and a checklist of DQIs applicable to certain types of needed information. A set of generic, defined DQIs was developed. Once the preliminary DQGs are defined, data acquisition can begin. Additional DQGs may be added as a result of the initial data analysis. If the quality of the data meet the requirements, work can proceed; if not, then one of several actions should be taken. Possible actions include obtaining better data, clearly defining the limitations of the data collected, performing sensitivity analysis to test the uncertainty, modifying the study purpose/scope, or stopping the study. (p. xix)

Two approaches were suggested for the evaluation of data quality: "qualitative evaluation using a matrix approach, and quantitative evaluation using value trees."

Research needs were identified in the categories of "(1) LCA, and particularly DQA [data quality assessment] framework development; (2) data and data base development and enhancement; and (3) advancement of mathematical models."

Field III, F.R., Isaacs, J. A., Clark, J. P. "Life Cycle Analysis and Its Role in Product and Process Development," *International Journal of Environmentally Conscious Design & Manufacturing*, 1993, Vol. 2, No. 2, pp. 13-20.

This article discusses LCA and its limitations based on decision analysis theory. The article also reviews the Swedish Environmental Priority Strategies (EPS) system, which was designed as a tool to evaluate the ecological impacts of alternative solutions. Its limitations have to do with the value assigned to the ecological factors which are based on the environmental objectives of the Swedish Parliament, and therefore may not applicable elsewhere. The authors state:

> While the EPS system is a commendable attempt at simplifying the enormous detail of inventory data to a representative environmental load, the developers of EPS have pointed out that this system is based on their subjective value judgments, which are not necessarily supportable in all situations worldwide. The ultimate goals set out by SETAC and the US EPA for improvement analysis based on life cycle inventories are laudable, but can only be realized by some kind of consensus on the values for avoiding environmental degradation.

Fiksel, Joseph. "Design for Environment: An Integrated Systems Approach," *Proceedings of the 1993 IEEE International Symposium on Electronics and the Environment,* Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1993, pp. 126-131.

The author defines design for environment (DFE) as "systematic consideration, during new product and process development, of design issues associated with environmental and human health and safety over the full product life cycle." Existing DFE methods include pollution and waste prevention, environmental management of materials, risk analysis, life-cycle costing, and system-oriented design. The author describes the current state of practice of DFE as opportunistic and project-specific. In order to establish DFE as a systematic component of product design and development, four elements are required: design metrics for quantification of environmental quality, design guidelines or rules for early implementation of environmental concerns, design verification methods for comparison to the metrics, and design decision frameworks to evaluate tradeoffs. The author presents the Integrated Life Cycle Model (ILCM), a conceptual model for a computer-based systems approach to DFE. The actual ILCM would be tailored to the specific products and processes of a company.

Fiksel, Joseph. "Quality Metrics in Design for Environment," *Total Quality Environmental Management*, Winter 1993/94, pp. 181-192.

The author defines design for environment (DFE) as "systematic consideration during new product and process development of design issues associated with environmental safety and health over the full product life cycle." The following list includes DFE practices common in industry today:

- Material substitution
- Waste source reduction
- Toxic use reduction

- Energy use reduction
- Life extension
- Design for separability and disassembly
- Design for disposability
- Design for recyclability
- Design for refurbishment
- Design for remanufacturing
- Design for energy recovery
- System-oriented design changes

Risk analysis techniques and life cycle analysis techniques are two types of tools that "contribute to the practice of DFE." The author believes that the use of quality metrics in DFE is essential to the achievement of environmental goals.

> In the context of DFE, environmental quality metrics are parameters used to measure design improvement with respect to environmental goals. Because of their fundamental role in the development process, quality metrics clearly are essential to the successful practice of DFE. Examples of environmental quality metrics that can be used to establish design objectives include:
>
> - Total energy consumed during the product life cycle
> - Renewable energy consumed during the product life cycle
> - Power used during operation (for electrical products)
> - Useful operating life (for discrete products)
> - Toxic or hazardous materials used in production
> - Total industrial waste generated during production
> - Hazardous waste generated during production or use
> - Air emissions and water effluents generated during production
> - Greenhouse gases and ozone-depleting substances released over life cycle
> - Product disassembly and recovery time (for discrete products)
> - Percentage of recycled materials used as input to the product
> - Percentage of recyclable materials available at end-of-life
> - Percentage of product recovered and reused
> - Purity of recyclable materials recovered
> - Percentage of product disposed or incinerated
> - Average life-cycle cost incurred by the manufacturer
> - Purchase and operating cost incurred by the customer
> - Fraction of packaging or containers recycled

The author classifies environmental quality metrics by the following three distinctions:

- Qualitative versus quantitative
- Absolute versus relative
- Source versus impact.

The author concludes with the following steps for introducing environmental quality metrics into its product and process development activities:

Development of metrics:

- Identify key company goals and objectives relevant to environmental performance.
- Select a reasonably small set of primary metrics that reflect the environmental goals.
- Derive corresponding operational metrics that are measurable and controllable.

Implementation of metrics:

- Establish systematic measurement tools for each of the DFE metrics selected.
- Develop an appropriate aggregation and weighting scheme.
- Assess the baseline environmental quality of existing products and processes.
- Track environmental quality improvements relative to the baseline.

Continuous improvement:

- Institutionalize the metrics and associated tools using computer support as appropriate.
- Benchmark environmental quality progress against competitors.
- Periodically establish new objectives for improvement.

Fiksel, Joseph and Wapman, Kenneth. "How To Design for Environment and Minimize Life Cycle Cost," *Proceedings of the 1994 IEEE International Symposium on Electronics and the Environment,* Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1994, pp. 75-80.

This article describes the principles and components of Design for Environment (DFE) and the tools needed to effectively integrate DFE into product development. The key elements needed for the DFE process include metrics, design practices, and analysis methods. The principle tools needed to support this process are on-line design guidance, performance assessment tools and integration with CAE/CAD framework. The article also discusses life cycle assessment and life cycle cost management.

Flynn, John E. "The Role of DFE in the Pollution Prevention Strategy of an Aerospace Producer," *Proceedings of the 1994 IEEE International Symposium on Electronics and the Environment,* Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1994, pp. 307-314.

This paper presents the Pratt & Whitney pollution prevention approach. Pratt & Whitney has established a Consolidated Pollution Prevention Team (CPPT) whose mission it is to establish a pollution prevention strategy. Within the CPPT, are three subteams: the Environmental Design Team, the Environment Technology Team and the Waste Minimization Steering Committee. The goals of the Waste Minimization Steering Committee are technology transfer, work share, common goal setting and common report formatting. The goals of the Environmental Technology Team are "identification of internal and customer needs, development of programs to meet these needs, matching of these programs with funding sources, and program execution on a time-line defined by the Pollution Prevention Plan." The Environmental Design Team is tasked with "eliminating environmental impacts at the earliest possible opportunity, during product life-cycle." This paper

focuses on the Environmental Design Team (EDT) and its approaches to ensure environmental considerations at the earliest stages of the design process.

Among the tools the EDT have developed are a training course entitled "Environmental Responsibilities for Designers," a "Environmental Design Consideration" manual for designers, and an integrated computer aided design system with environmental information. The EDT is assessing the availability of more complex life cycle analysis tools.

Fouhy, Ken. "Life Cycle Analysis Sets New Priorities," *Chemical Engineering*, July 1993, pp. 30-34.

This article describes life cycle analysis and gives some examples of applications and limitations of the approach. The author notes that LCA may become a part of Total Quality Management programs, and that LCA is becoming part of strategic planning.

Glantschnig, Werner J. "Green Design: A Review of Issues and Challenges, "Proceedings *of the 1993 IEEE International Symposium on Electronics and the Environment*, Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1993, pp. 74-78.

This paper discusses the complex issues and challenges of green design.

Gosh, John. "Germany's 'Green TV' Signals Trend in Set Design," *Electronics*, July 1992, p. 29.

This short article highlights an ongoing cooperative effort in Germany between five TV set makers to develop a "green" TV. This TV will be designed so that it can be easily disassembled and the parts recycled at the end of its useful life. Each company has been assigned a specific task: one is investigating selection of the "right" materials and production techniques, one is investigating construction problems, one is investigating ease of disassembly, one is investigating recyclability of picture tubes and loudspeakers, and the last is investigating recycling of coils and other assemblies.

This cooperative effort is in response to Germany's recent "take back" legislation which requires equipment makers of TVs and other electronic equipment to take back the used equipment for recycling.

Graedel, T. E. "Prioritizing Impacts: The Second Stage of Life Cycle Assessment," *Proceedings of the 1994 IEEE International Symposium on Electronics and the Environment*, Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1994, pp. 89-93.

The author discusses the impact assessment stage of life cycle assessment and provides examples of prioritization schemes and their effect on the analysis. Impact assessment takes the information developed in the inventory analysis (first stage of life cycle assessment) and assigns relative values or weights to the data according to their impact on the environment. There are at least five ranking systems under development for impact assessment. "All share the same general approach in that they compile the materials and processes used in making a product, multiply those activities by environmental impact factors, and sum the result for one or more different stages in the product life cycle."

Graedel, T. E., & Allenby, B. R. *Industrial Ecology*, Englewood Cliffs, NJ: Prentice Hall, 1995.

This book is written as a textbook in Industrial Ecology. It is separated into five sections: introductory topics, relevant "external" factors, evaluating life cycles, design for environment, and forward looking topics. The authors define industrial ecology in the following paragraph:

> Industrial ecology is the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal. Factors to be optimized include resources, energy, and capital.

The authors devote several chapters of this book to life cycle assessment (LCA) and some of the published methods in performing LCAs. The authors differentiate between LCA and design for environment (DFE). They define LCA as "a *specific protocol*, in that in its optimum embodiment, it determines where products, processes, or facilities are less than environmentally meritorious and ranks the environmental impacts of those specific situations." They view DFE as follows:

> After the materials flows and environmental impacts of a product or a process have been assessed, the next step is to design a strategy for improvement. The techniques for doing so are generically called "design for environment" (DFE). DFE approaches can be designated *generic,* in that they refer to generally meritorious actions or considerations, and encourage their incorporation into product or process design activities in much the same vein as would be considerations of flow magnitudes or materials costs.

In their chapter on industrial design of products and processes, the authors differentiate between the product design and the process design. Industrial ecology involves both processes and products, however, the designers of each are usually different. In addition, processes can be embedded in an industry and take a long time to replace with another process. Products are much easier to replace or redesign. The authors discuss both industrial process design and industrial product design and their application in industrial ecology. Of interest is the authors viewpoint that design for environment (DFE) embodies product design methodologies.

Of interest for this literature review is the authors' examination of the U. S. EPA's Science Advisory Committee report, "Reducing risk; Setting priorities and strategies for environmental protection." Since this report was not obtained for this literature review, the following is quoted from this book, p. 152:

> One of the first useful exercises in setting priorities on environmental impacts was a 1990 effort of the U. S. EPA's Science Advisory Committee. This committee prioritized impacts with the goal of providing advice to EPA on the best use of its resources. Several ranking parameters were used to sort environmental impacts into priority order:

- The spatial scale of the impact (large scales being worse than small).
- The severity of the hazard (more toxic substances being of more concern than less toxic substances).
- The degree of exposure (well-sequestered substances being of less concern than readily mobilized substances).
- The penalty for being wrong (longer remediation times being of more concern than shorter times).

Given this general approach to ranking environmental hazards, the committee produced the following lists:

Relatively High-Risk Problems:

- Habitat alteration and destruction
- Species extinction and overall loss of biological diversity
- Stratospheric ozone depletion
- Global climate change

Relatively Medium-Risk Problems:

- Herbicides/pesticides
- Toxics, nutrients, biochemical oxygen demand, and turbidity in surface waters
- Acid deposition
- Airborne toxics, including smog-related constituents

Relatively Low-Risk Problems:

- Oil spills
- Groundwater pollution
- Radionuclides
- Acid runoff to surface waters
- Thermal pollution

Hermann, Ferdinand. "Environmental Considerations for Product Design for the German Market," *Design for Manufacturability 1994: An Environment for Improving Design and Designing to Improve Our Environment,* New York: The American Society of Mechanical Engineers, 1994, pp. 35-48.

The author describes the environmental background of the European community and Germany, their regulatory trends and eco-labeling schemes.

Hundal, M. S. DFE: Current Status and Challenges for the Future," *Design for Manufacturability 1994: An Environment for Improving Design and Designing to Improve Our Environment,* New York: The American Society of Mechanical Engineers, 1994, pp. 89-98.

This paper reviews the literature on design for environment (DFE) as well as the current environmental legislation in several countries. The effect of DFE on the various steps of the design process is discussed. Recycling and remanufacturing are discussed. The steps for the remanufacturing process are: disassembly, cleaning, sorting, checking, reconditioning, and reassembly. These steps are discussed in more detail and examples of companies currently remanufacturing are presented.

Keldmann, Troels, and Olesen, Jesper. "Managing the Environmental Issue in Product Development: the Environmentally Oriented Milestone Questions and Techniques," *Design for Manufacturability 1994: An Environment for Improving Design and Designing to Improve Our Environment,* New York: The American Society of Mechanical Engineers, 1994, pp. 99-106.

The authors present a phase structure for product development that includes identification and categorization of environmentally oriented milestone questions. They found the following conclusions from the application of this structure:

1. The environmental goals come from the interpretation of the company policy, the market and legislational data.
2. The environmental goals are supplemented or further detailed as the product and the life cycle of the product are synthesized.
3. Almost all milestone questions can be answered without the use of methods and tools.
4. Few of the milestone questions require the use of life cycle assessment.
5. It is not obligatory to answer all milestone questions.
6. The milestone questions and the categorizations offer a pattern for methods.

Keoleian, G., Glantschnig, W., and McCann, W. "Life Cycle Design: AT&T Demonstration Project," *Proceedings of the 1994 IEEE International Symposium on Electronics and the Environment*, Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1994, pp. 134-135H.

The life cycle design process, developed for the U. S. EPA by the principle author and the University of Michigan, was used as a framework for this demonstration project for an AT&T business phone. The purpose of the project was to explore the feasibility and applicability of the life cycle design framework that was developed under the separate contract with the EPA. The demonstration project utilized the life cycle design multicriteria matrix which includes environmental, performance, cost, cultural, and legal elements.

Keoleian, Gregory A. and Menerey, Dan. *Life Cycle Design Guidance Manual: Environmental Requirements and the Product System*, (Report No. EPA/600/R-92/226), Cincinnati, OH: Risk Reduction Engineering Laboratory, Office of Research and Development, U. S. Environmental Protection Agency, 1993.

This manual provides guidance for developing new products according to a life cycle approach which considers environmental impacts of all stages of a product's life cycle. The authors define life cycle design and state its goals in the following paragraphs:

> Life cycle design is the application of the life cycle framework to product system design. The product system includes product, process, distribution, and management/information components.
>
> The goal of life cycle design is to minimize aggregate risks and impacts over this life cycle. This goal can only be attained through the balancing of environmental, performance, cost, cultural, legal, and technical requirements of the product system. Concepts such as concurrent design, total quality management, cross-disciplinary teams, and multi-attribute

decision making are essential elements of the life cycle design that help meet these goals.

This manual contains the following as topics for chapters:

- Introduction
- Life cycle design basics
- The development process
- Design requirements
- Design strategies
- Environmental analysis tools
- Life cycle accounting

This manual goes into detail on the development process of a new product and explains how life cycle design provides a framework for this process.

> Life cycle design is a logical extension of concurrent manufacturing, a procedure based on simultaneous design of product features and manufacturing processes. In contrast to projects that isolate design groups from each other, concurrent design brings participants together in a single team. By having all actors in the life cycle participate in a project from the outset, problems that develop between different disciplines can be reduced.

Environmental design strategies include examining product system life extension, material life extension, material selection, reduced material intensiveness, process management, efficient distribution, and improved management practices. The chapter on environmental analysis tools addresses the steps in life cycle assessment.

The authors make the following distinction between life cycle design and life cycle assessment:

> Life cycle design should not be confused with life cycle assessment. Rather than concentrating on only analytical tasks, life cycle design provides a framework and guidelines for integrating environmental requirements into product development. Life cycle assessment may improve environmental evaluation, but all environmental, performance, cost, cultural, and legal requirements must still be balanced in successful products.

The final chapter on life cycle accounting addresses the deficiencies of traditional accounting methods and presents life cycle accounting as a tool to examine usual costs, hidden costs, liability costs, as well as, less tangible costs.

Korpalski, Tom. "Pragmatic Use of Priority Life Cycle Assessment Elements To Help Drive Product Stewardship," *Proceedings of the 1994 IEEE International Symposium on Electronics and the Environment*, Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1994, pp. 207-210.

The Computer Products Division at Hewlett-Packard has developed a set of metrics which provide management with a method of monitoring progress in life cycle assessment. These metrics are divided into two categories, 1) product, consumables, packaging, and learning products, and 2) manufacturing process emissions. The first category is further divided into the following subcategories: materials conservation/waste reduction, energy efficiency, and design for environment. No weighting of these parameters was attempted. This method is valuable when trying to improve a design. It may not be valid when comparing

alternative designs, since the emphasis is on improving any item, which would improve the product.

Kuuva, Markku and Airila, Mauri. "Conceptual Approach on Design for Practical Product Recycling," *Design for Manufacturability 1994: An Environment for Improving Design and Designing to Improve Our Environment,* New York: The American Society of Mechanical Engineers, 1994, pp. 65-76.

The authors present a conceptual approach to Design for Recycling (DFR) as one component of Design for the Environment (DFE). They point out that DFR must begin at the product concept stage in order to choose whether to make use of existing recycling practices or to develop an independent recycling strategy. The authors present guidelines concerning disassembly of a product aimed at materials recycling:

1. Minimize the number of parts.
2. Standardize and use modular constructions.
3. Place the components in logical groups according to their intended recycling strategy and the handling sequence in the disassembly process.
4. Avoid integral constructions and unnecessary combinations of different materials, reduce the number of non-recyclable materials and components.
5. Ensure that the coatings, paints etc. that are used do not present any problems.
6. Make the joints, gripping points, breaking points etc. easily accessible.
7. Ensure that the disassembly can be made with conventional tools and equipment without special arrangements.
8. Provide a technique to safely dispose of hazardous waste possibly to be found in the product.

Legarth, J., Alting, L., Erichsen, H., Gregersen, J., and Jorgensen, J. "Development of Environmental Guidelines for Electronic Appliances," *Proceedings of the 1994 IEEE International Symposium on Electronics and the Environment*, Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1994, pp. 69-74.

This paper provides two electronic product examples of how to develop environmental guidelines from life cycle assessment methods.

Lifset, Reid. "Raising the Ante for Life Cycle Analysis," *BioCycle*, April 1991, pp. 76-77.

The author points out the "partisanship" of an LCA in that the results could easily reflect the wishes of the sponsor. A variety of organizations are working to develop a definitive methodology for LCA. In the meantime, the author suggests three questions to pose of any LCA to maximize its reliability:

1. Are the methodology and the data publicly available?
2. Was the study peer reviewed?
3. Was a sensitivity analysis performed?

Lowe, Ernest. "Industrial Ecology—An Organizing Framework for Environmental Management," *Total Quality Environmental Management,* Autumn 1993, pp. 73-85.

Mr. Lowe defines industrial ecology as a "systemic organizing framework for the many facets of environmental management." Industrial ecology considers the natural environment as a model for the solution of environmental problems. The author cites recent applications of cooperative initiatives between companies so that one's waste is another's raw material, or energy resource. The examples "suggest the power of moving beyond individual company or plant boundaries to seek improvements in performance of larger systems." The author lists the following natural ecosystem characteristics as ones to emulate in an industrial environment:

- In the natural system there is no such thing as "waste" in the sense of something that cannot be absorbed constructively somewhere else in the system.
- Nutrients for one species are derived from the death and decay of another.
- Concentrate toxins are not stored or transported in bulk at system level but are synthesized and used as needed only by species individuals.
- Materials are continually circulated and transformed in extremely elegant ways. The system runs entirely on ambient solar energy, and over time it has actually managed to store energy in the form of fossil fuel.
- The natural system is dynamic and information driven, and the identity of ecosystem players is defined in process terms.
- The system permits independent activity on the part of each individual of a species, yet cooperatively meshes the activity patterns of all species. Cooperation and competition are interlinked and held in balance.
- In ecosystems, efficiency and productivity are in dynamic balance with resiliency. Emphasis of the first two qualities over the third creates brittle systems, likely to crash.
- Each member of an ecosystem performs multiple functions.

The author lists three major challenges in design for environment, i.e., lack of materials database with reliable environmental impact information, need of a complex organization system to manage design for environment, and involvement of society in defining values for design tradeoff analysis.

The author .lists and describes five "streams of work" ongoing in Industrial Ecology. They are design for environment, industrial metabolism, structural economics, system management of interface between industry and natural systems, and environmental information systems with feedback capabilities.

"Industrial metabolism has developed as a big-picture analytic tool capable of looking at the total pattern of energy/materials flows from initial extraction of resources to final disposal of wastes."

Structural economics builds on industrial metabolism by applying input-output models which help analyze alternative scenarios for industrial change.

The last two, a system management interface and the information systems feedback appear to be broad conceptions that would relate to a dynamic management system and the management tools used to interpret the data generated by the system.

Maxie, Eddie. "Supplier Performance and the Environment, *Proceedings of the 1994 IEEE International Symposium on Electronics and the Environment,* Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1994, pp. 75-80.

Hewlett-Packard Company has developed performance expectations for their suppliers based on technology, quality, responsiveness, delivery, cost and the environment (TQRDC-E). Each potential supplier is rated from zero to four on each of these six items, with four being the best rating. An average overall rating is calculated as the score for each supplier. For the E rating, an example might include three environmental questions, each carrying a certain weight. An example question might be "has the supplier eliminated the use of ozone depleting substances?" A yes response would gain a four rating. A no response would get a zero. The question might hold a 30 percent weight in comparison to the other three questions.

McGee, E. Craig and Bhushan, Abhay K. "Applying the Baldrige Quality Criteria to Environmental Performance: Lessons from Leading Organizations," *Total Quality Environmental Management,* Autumn 1993, pp. 1-18.

In addition to technical solutions to environmental challenges, new approaches to management and organizational systems are needed in order to implement the technical solutions. The authors propose the use of the Malcolm Baldrige National Quality Award criteria as a framework for integrating environmental management with Total Quality Management (TQM) philosophy. The Baldrige criteria consist of seven areas or organizational excellence: leadership, human resources utilization, information and analysis, strategic quality planning, quality assurance, quality results, and customer satisfaction.

> The leadership category consists of all those activities that senior executives perform to promote environmental responsibility within the company and among the external community. These include:
>
> - Creating and diffusing a corporate environmental, health, and safety policy
> - Making environmental responsibility a criteria for management performance and linking it to salary and bonus awards.
> - Providing internal funding for development of environmentally safe products and processes.

The human resources utilization category "concerns how the talents and abilities of the work force are utilized."

The information and analysis category "consists of the measurement systems that the company utilizes to evaluate its environmental impact."

Strategic quality planning involves ensuring that quality (in this case, environmental quality) is an important criteria for strategic planning efforts.

The quality assurance category instills the philosophy of continuous improvement in the materials and manufacturing processes.

> Compliance with state and government regulations becomes the minimum performance level. Continuous improvement energizes organizations to go *beyond compliance,* looking for ways to reduce emissions, to cut energy use, and improve safety and health practices.

The quality results category measures environmental performance of the company. Broad indicators of environmental performance include:

- Landfill mass
- Energy, fuel, and water conservation
- Support of community efforts
- The percentage of a product that is recycled or reused
- Elimination of CFCs
- Lost-time accident and health indices
- Product liability claims

Customer satisfaction includes different customer groups: "direct consumers, employees and family members, the community, OSHA, EPA, and ultimately, the planet."

The authors present all these criteria with examples of implementation at Xerox, Monsanto, Pacific Gas & Electric, AT&T, and Digital Equipment Corporation.

O'Dea, Katherine, and Freeman, Gregg. "Environmental Logistics Engineering: A New Approach to Industrial Ecology," *Total Quality Environmental Management,* Summer 1995, pp. 73-85.

Logistics engineering considers the full life cycle of a product system during the system's conceptual phase. Environmental considerations are now beginning to be added to the list of considerations in the logistics process. The authors feel logistics should be "considered a keystone for the design, development, operation, maintenance, eco-support, and eventual retirement of eco-industrial parks and other environmental quality projects." Eco-industrial parks are industrial parks where the inhabitants collaborate in the ecological resolution of resources, energy, hazardous materials waste recycling and disposal, distribution, and other pertinent industrial ecology issues.

> Integrated Logistics Support (ILS) is a synthesis of analysis, planning, and management tools and methodologies. It has been developed for the cost-effective acquisition, highly reliable design, and management of very large-scale product systems, such as eco-industrial parks...The practice of ILS remains the only proven approach that systematically integrates the many downstream (eco-supportable) requirements of a product system into comprehensive front-end planning.

The authors suggest that the ILS approach can be adapted to become Integrated Logistics Eco-Support (ILES). The 12 traditional elements of ILS can be reduced to five elements of ILES. These recommended elements are:

1. The Integrated Logistics Support Plan (includes specifications)
2. The Logistics Support Analysis and compilation of its output: the Logistics Support Analysis Record.
3. Life-Cycle Cost Analysis
4. "-ility" Engineering (designing-in eco-supportability)
5. Reverse Logistics (a subset of eco-support)

The authors examine each of these five elements and how they might be applied in the design of an eco-industrial park.

Overby, Charles M. "QFD & Taguchi for the Entire Life Cycle," *Annual Quality Congress Transactions*, Milwaukee, WI: ASQC, 1991, pp. 433-438.

Dr. Overby theorizes that ideas regarding defect prevention through quality design, such as Quality Function Deployment (QFD) and Taguchi methods, may be transferred for use in concepts of pollution prevention through design.

Parker, Jean E., & Boyd, Beverly, L. "An Introduction to EPA's Design for the Environment Program," *Proceedings of the 1993 IEEE International Symposium on Electronics and the Environment*, Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1993, pp. 144-150).

The EPA's design for the environment (DFE) program has initiated projects which operate through three levels of involvement: infrastructure projects aimed at changing general business practices, industry projects with trade associations and businesses to evaluate risks, performance, and costs of alternatives, and facility-based programs to help individual business in their environmental design efforts.

Rethmeyer, Douglas A. "The Role of Life Cycle Analysis in Considering Product Change," *Waste Management*, Vol. 13, 1993, pp. 351-352.

The first step of life cycle analysis, life cycle inventory, is presented in this article as the Resource and Environmental Profile Analysis (REPA). A REPA "examines the quantifiable direct and indirect effects that occur in the environment due to the existence of manufactured products."

> A REPA is not a risk assessment or impact analysis . Health and toxicological issues relating to the impact of various pollutants on human and animal tissue are not addressed.

A REPA examines raw materials, energy consumption, and water usage as inputs. Outputs include products, coproducts, energy production, and the emissions: solid waste, air pollutants, and water pollutants. A computer model is used to process the data. REPA includes the following five steps: define the project, gather all data, create a computer model, tabulate the results, and analyze the results.

> Sources of REPA data include actual operating data provided by industry, government documents, textbooks and other literature. The most reliable data are actual operating data from industry, which are usually current and include information on discharge of emissions after treatment.

Rhodes, Stanley P. "Applications of Life Cycle Assessment in the Electronics Industry for Product Design and Marketing Claims," *Proceedings of the 1993 IEEE International Symposium on Electronics and the Environment*, Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1993, pp. 101-105.

This paper describes life cycle assessment and relates it to applications in the electronics industry.

Ryberg, Betty A. "Design for Environmental Quality: Reap the Benefits of Closing the Design Loop," *Proceedings of the 1993 IEEE International Symposium on Electronics and the Environment*, Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1993, pp. 37-42.

This paper presents a framework for implementing a Design for Environmental Quality (DFEQ) at Pitney Bowes. The goals of the DFEQ program at Pitney

Bowes are: minimize environmental impacts, minimize manufacturing employee exposure to hazardous materials, conserve energy and materials, and maximize reuse and recycling opportunities. Pitney Bowes has identified the need for the following tools in order to successfully implement a DFEQ program: a design guide, a design manual, an inventory matrix, and software.

Salomon, Lt. Col. Roy K. "Implementing Pollution Prevention in DoD System Acquisition Programs—What More Is Needed," *Proceedings of the 1994 IEEE International Symposium on Electronics and the Environment*, Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1994, pp. 45-50.

The author describes three pollution prevention paradigms currently used within the aerospace industry. The companies involved are Lockheed Aeronautical Systems Company (LASC), Lockheed Fort Worth Company (LFWC), and McDonnell Douglas Aerospace - East (MDA-E).

LASC utilizes an identification-evaluation paradigm for their F-22 Advanced Tactical fighter, Engineering and Manufacturing Development (EMD) program. The key steps are to identify hazardous materials and evaluate the benefits, risks, and alternatives early in the design process.

MDA-E utilizes a strategic-planning paradigm that defines what must be done, when it must be done, why, and how much it will cost. A compliance plan is formulated based on directives analysis, facility analysis, and contractor analysis. The next steps are developing an implementation plan, and evaluating impact on resources. These are input to the final business plan.

LFWC uses a goal-assessment paradigm. The steps to this process are in a repeating loop and include setting program goals and evaluating progress, assessment, feasibility analysis, and implementation.

The author goes on to evaluate each of the three paradigms and their implications for the DoD system acquisition policy. The author found that each of the paradigms falls short of evaluating the entire system life cycle. He also found that "one or more government inputs were absent (including environmental requirements, criteria, and goals) reducing the effectiveness of each approach. To improve the implementation of pollution prevention in system acquisition programs, DoD policy must be [sic] ensure new environmental regulations are addressed and missing government inputs are provided."

Schutzenberger, Chris. "An Electronic, On-Line Database for Quantitative Environmental Assessment of New Designs," *Proceedings of the 1994 IEEE International Symposium on Electronics and the Environment*, Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1994, pp. 183-186.

Hughes Radar Systems has developed the Green Notes Environmental Rating and Measurement System. It consists of a database that contains a "green" value for each manufacturing process. When a new product is designed with numerous processes, the System adds up the green values for a total green number for the product. For each process, the System can suggest an alternative process with a better green value, so that the designers can evaluate and make changes to their design. The green values were assigned by a multi-disciplinary team, who rated each manufacturing process in the database according to the following characteristics: flammability, air quality, water quality, solids/waste disposal, irritant level, associated processes and controls, quantities required, Proposition 65 listing, and potential future regulations. A composite rating for each process was

calculated using an algorithm developed by the team. The rating includes only environmental, health, and safety factors; it does not evaluate design considerations, such as, strength, hardness, etc.

Steinhilper, Rolf. "Design for Recycling and Remanufacturing of Mechatronic and Electronic Products: Challenges, Solutions and Practical Examples from the European Viewpoint," *Design for Manufacturability 1994: An Environment for Improving Design and Designing to Improve Our Environment*, New York: The American Society of Mechanical Engineers, 1994, pp. 65-76.

The author describes the problem of the mounting waste and scrap generated by the electronics industry, i.e., computers, household appliances, etc. The Fraunhofer-Institute for Manufacturing Engineering and Automation has developed a comprehensive concept for product recycling that contains the following five steps:

1. Recording and thorough analysis of the product range and recycling tasks.
2. Determination of the recyclability of specific products and their subassemblies.
3. Planning of return logistics and information flows between production and recycling processes.
4. Development and dimensioning of reliable and future-oriented solutions for disassembling and recycling.
5. Guidelines for recycling-friendly design of future products.

The author gives examples of companies that recycle complex technical products by remanufacturing, rebuilding and reconditioning activities.

Sullivan, John L., and Young, Steven B. "Life Cycle Analysis/Assessment," *Advanced Materials & Processes*, February 1995, pp. 37-40.

This article provides a description of life cycle analysis, including the steps of LCA. It also states that technical documents on life cycle analysis have been published by the Environmental Protection Agency (EPA), the Society of Environmental Toxicology and Chemistry (SETAC), and the Canadian Standards Association (CSA). Viewpoints by the authors include:

> For meaningful comparisons of the life cycle performance of competing and/or evolving product systems, it is important that associated LCAs be conducted consistently, using the same standards. Although the common methodologies developed by SETAC, EPA, and CSA are a step in that direction, a broad-based international standard is needed. Such an effort is being undertaken by ISO 14000 (TC 207).
>
> ...It is in this stage [life cycle inventory] that the various inputs and outputs (energy, wastes, resources) are quantified for each phase of the life cycle...The separation of burdens (inputs and outputs) for each stage facilitates improvement analysis.
>
> Impact analysis is a process by which the environmental burdens identified in the inventory stage of an LCA are quantitatively or qualitatively characterized as to their effects on local and global environments.

Improvement analysis is the stage of LCA that has received the least attention. Basically, it represents a process within LCA that leads to identifying chances for environmental improvement. LCA improvement is an activity of product-focused pollution prevention and resource conservation. Opportunities for improvement arise throughout an LCA study. Improvement analysis is often associated with Design For the Environment (DFE) or Total Quality Management (TQM).

To the authors' knowledge, a complete Life Cycle Assessment has not been conducted to date. Most studies that purport to be LCAs are in actuality LCIs. [life cycle inventories]

Thompson, Barbara C. and Rauck, Albert C. "Applying TQEM Practices to Pollution Prevention at AT&T's Columbus Works Plant," *Total Quality Environmental Management*, Summer 1993, pp. 373-381.

This article illustrates the application of TQM (total quality management) practices at an AT&T plant. TQM applied to environmental management problems is currently referred to as TQEM (total quality environmental management). AT&T emphasizes the following five principles of TQM:

- The customer comes first.
- Quality happens through people.
- Prevention through planning.
- All work is part of a process.
- Quality improvement never ends.
- Suppliers are an integral part of our process.

In 1990, AT&T chairman Bob Allen announced several worldwide environmental goals for the company. The Columbus Works Plant choose to concentrate on his goal of reduction of toxic air emissions.

In this case study, AT&T used policy deployment, a TQM practice. Policy deployment consists of three steps: 1) policy establishment by top management, 2) policy deployment to middle management, and 3) policy implementation by work teams.

The Columbus Works Plant choose as their demonstration project, reduction of the use of 1,1,1-trichloroethane (TCA). The teams goals were to achieve 50% reduction by 1993 and elimination by 1995. "During the course of the project, the team identified solutions for 75 percent of the Columbus Works TCA uses."

As a result of this work, the AT&T team concluded the following elements are essential for a successful pollution prevention program:

- Commitment from top management is essential and must be communicated to all employees.
- Generation of potential wastes is a part of the manufacturing process and must be addressed as are other process elements.
- Pollution prevention is amenable to TQM procedures and practices.
- Small successes in pollution prevention are easy to achieve and add to a successful overall program.

- Regulatory controls will continue to increase, so pollution prevention accomplished today will bring savings tomorrow.
- The best time to consider environmental impact is during product and process design.

Thurston, Deborah L. "Internalizing Environmental Impacts in Design," *Design for Manufacturability 1994: An Environment for Improving Design and Designing to Improve Our Environment*, New York: The American Society of Mechanical Engineers, 1994, pp. 107-113.

The author presents a methodology that integrates life cycle design, multiattribute design evaluation, and internalization of environmental impacts into the design process. The author also presents an example of material selection in the automotive industry.

Tolle, Duane, Salveta, Karen, et al. "Development and Assessment of a Pre-LCA Tool," *Proceedings of the 1994 IEEE International Symposium on Electronics and the Environment*, Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1994, pp. 201-206.

The P-LCA method is a streamlined approach to life cycle assessment (LCA). The P-LCA tool was developed for use at Digital Equipment Corporation and was based on the Environmental Profile Screening (EPS) system developed by Battelle. The products that were assessed by this tool were broken down into a mix of subassemblies and component parts. Each of these parts were rated by environmental criteria which were in turn assessed a weight of relative importance based on Battelle's assessment of the environmental significance. For example the criteria might be a score for the emissions of a toxic substance based on a measured metric. The weight that this toxic emission would receive would be based on Battelle's understanding of the importance of that environmental concern. The output of the analysis is a matrix whereby a "multiplication of the individual criterion score by its relative weight factor followed by summing over all of the physical components of the product yields a single environmental figure of merit." A visual inspection of the matrix would also identify areas of potential for improvement.

U. S. Army Acquisition Pollution Prevention Support Office. *Material developer's guide for pollution prevention, second edition—1994*, Washington, DC: Secretary of the Army Installations, Logistics, and Environment; Secretary of the Army Research, Development, and Acquisition; Headquarters—Army Materiel Command, 1994.

This guide is written for the materiel developer and describes the Army's environmental program, focusing on the pollution prevention pillar. The guide states that "pollution prevention is the only environmental management approach that can reduce your life cycle costs, minimize schedule risks, and improve overall system performance." The guide summarizes current international treaties, federal environmental regulations, Executive Orders, DoD Directives, and Army regulations that have an impact on Army acquisition policy. The guide offers guidelines and checklists to assist the materiel developer in developing his/her pollution prevention program for the acquisition life cycle. This guide examines each step in the acquisition life cycle and illustrates the impact of a pollution prevention program at each step. The appendices offer additional resource information including state pollution prevention requirements and program contacts, international pollution prevention program contacts, Army training and technical resources, and federal information resources.

Vigon, Bruce W. and Curran, Mary Ann. "Life-Cycle Improvements Analysis: Procedure Development and Demonstration," *Proceedings of the 1993 IEEE International Symposium on Electronics and the Environment*, Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1993, pp. 151-156.

The life cycle assessment approach consists of four components: goal definition and scoping, inventory, impact analysis and improvements analysis. This paper examines the improvements analysis process. An improvements analysis would include the following elements: identification of potential improvement areas, selection of team members, application of a process for identification and screening of alternatives, development of decision data for balancing cost and other factors, analysis of alternatives, and development of an implementation plan.

Vigon, Tolle, Cornaby, Latham, Harrison, Boguski, Hunt, and Sellers. *Life-Cycle Assessment: Inventory Guidelines and Principles*, (Report No. EPA/600/R-92/245). Cincinnati, OH: Risk Reduction Engineering Laboratory, Office of Research and Development, U. S. Environmental Protection Agency, 1992.

This document provides a methodology to be followed by interested organizations for the inventory analysis step of the life-cycle assessment process. An overview of the life-cycle assessment (LCA) process is presented and the three components of LCA, namely, inventory analysis, impact analysis, and improvement analysis are described. The authors recognize that some researchers include a fourth component, goal definition and scoping, however that component is actually the first step of the inventory analysis. Subsequent steps of the inventory analysis include gathering and developing data, presenting and reviewing data, and interpreting and communicating results.

This document focuses on the above steps to be taken during an inventory analysis, leaving the impact analysis and improvement analysis procedures for future documents. The document also addresses issues such as transportation, coproduct issues, data issues, various system boundaries, and geographical issues.

The authors define life-cycle assessment as a concept that evaluates "the environmental effects associated with any given activity from the initial gathering of raw material from the earth until the point at which all residuals are returned to the earth."

Life cycle stages are defined as raw material acquisition, manufacturing, use/reuse/maintenance, and recycle/waste management. The manufacturing step is further divided into materials manufacture, product fabrication, and filling/packaging/distribution.

Warren, John L., and Weitz, Keith A. "Development of an Integrated Life-Cycle Cost Assessment Model," *Proceedings of the 1994 IEEE International Symposium on Electronics and the Environment*, Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1994, pp. 155-163.

The authors introduce a conceptual framework for a life cycle cost assessment model (LCCA). It was developed using the foundation of the life cycle assessment (LCA) models developed by the U.S. Environmental Protection Agency (EPA) and the Society of Environmental Toxicology and Chemistry (SETAC). The LCA approach relates four components, goal definition and scoping, inventory analysis, impact assessment, and improvement assessment. Goal definition identifies the overall purpose of the LCA. Scoping identifies the boundaries, assumptions, and limitations of the LCA. Inventory analysis provides information on the inputs and

outputs of a system. Impact assessment is still "in its infancy and has only been conceptually defined..[and]... improvement assessment is the least developed component of LCA."

Life cycle costs are categorized as conventional costs, liability costs, and environmental costs. Conventional costs are the dollar costs associated with most cost accounting systems, such as capital, equipment, labor, energy, etc. Liability costs are costs associated with some future liability potential, such as legal counsel, penalties/fines, personal injury, remediation, etc. Environmental costs are those costs associated with the impact of the system on the environment, such as, global warming, ozone depletion, water pollution, chronic health effects, habitat alteration, etc.

According to the authors,

> Life-cycle cost assessment (LCCA) provides a means for integrating economic and environmental cost information into the LCA framework to provide an *a priori* overview of life-cycle cost. In this paper, we define LCCA as a systematic process for evaluating the life-cycle economic and environmental costs of a system by identifying life-cycle cost items, assigning measures of value to those items, and evaluating options for reducing the total life-cycle cost and optimizing the use of scarce resources.

The authors define a life-cycle cost integration model (LCM) as a "proposed computer-based decision support tool that allows the user to assess—in an integrated approach—the costs and environmental effects associated with the life cycle of a product, process, project, or activity." This model contains four levels, project scoping, data acquisition, data compilation and analysis, and opportunities analysis. The next step in this research is to test the LCCA methodology and a test version of LCM using a specific project.

Wells, Richard, and Calkins, Patricia. "Measuring Environmental Performance," *Proceedings of the 1994 IEEE International Symposium on Electronics and the Environment*, Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1994, pp. 53-57.

The authors describe a management and measurement tool used at J. M. Huber Corp. called the Huber Environmental Performance Index (HEPI) which allows Huber to track environmental process across 12 different divisions. It assigns weights to various factors to assist in value decisions. First, Huber categorizes environmental impacts by the kind of impacts that are affected, specifically, community welfare, global/regional welfare, resource efficiency, and compliance assurances. Within each of these dimensions, the degree of hazard is weighted. Management practices affect the weighting, as well. The HEPI provides a "comprehensive, consistently prepared profile of actual and potential environmental impacts across Huber's extremely diverse operations." Although originally developed for manufacturing operations, HEPI provides a framework for Life Cycle Assessment of environmental impacts.

Wenzel, H., Hauschild, B., Jorgensen, J., and Alting, L. "Environmental Tools in Product Development, *Proceedings of the 1994 IEEE International Symposium on Electronics and the Environment*, Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1994, pp. 100-105.

The Danish Environmental Protection Agency has sponsored a program entitled the Environmental Design of Industrial Products. The prime contractor is The Life

Cycle Centre at the Institute for Product Development at the Technical University of Denmark. Participating industrial companies are: Bang & Olufsen Ltd., Danfoss Ltd., Gram Ltd., Grundfos Ltd., and KEW Industries Ltd. This paper presents the tools and methods developed by the design team for support of environmental criteria in product development. Their approach is based on the Life Cycle Concept which maintains that the product must be designed and developed within an environmental framework for all life cycle phases, including, raw material acquisition, material production, product manufacturing, usage, disposal/recycling and transportation.

The environmental tools that are described in this report include: environmental polices, life cycle modeling, life cycle inventory, life cycle assessment, life cycle diagnosis, environmental design strategies, environmental specifications, environmental and design rules, life cycle modeling inventory and assessment of concepts/components, and life cycle assessment - new products.

Environmental polices are the company's overall guidelines on the environmental criteria for product development.

Life cycle modeling provides a framework for describing the life cycle of a new product. A similar product may be used as a model to represent the product under development. The output of a life cycle model is a model of the life cycle for each component of the product.

Life cycle inventory provides a guideline for data collection of energy consumption, material consumption, emissions and occupational health.

Life cycle assessment translates the data collected during the life cycle inventory and translates it into potential environmental effects, resource consumptions, and occupational health effects.

Life cycle diagnosis takes the assessment criteria and analyzes environmental improvement potential throughout the life cycle of the product.

Environmental design strategies analyzes the environmental benefit of overall design strategies.

Environmental specifications are developed for the new product.

Environmental and design rules are developed which contain checklists, principles and examples for basic knowledge to be applied to all products.

Life cycle modeling, inventory and assessment of concepts/components are simplified tools as described above for rough modeling of the life cycle.

Life cycle assessment - new products updates the modeling input and is used for documentation of the overall environmental company policy.

Wixom, Michael R. "The NCMS Green Design Advisor, A CAE Tool for Environmentally Conscious Design," *Proceedings of the 1994 IEEE International Symposium on Electronics and the Environment*, Piscataway, New Jersey: The Institute of Electrical and Electronics Engineers, Inc., 1994, pp. 179-182.

The Green Design Advisor is being developed by the National Center for Manufacturing Science (NCMS) and its member companies. This Advisor is a Computer Aided Engineering tool that will be used by design and manufacturing engineers in evaluating the environmental impacts of their products and processes early in the development stage. Six user needs have been identified: minimize data input requirements, demonstrate cost benefits, address federal procurement standards, compare options within particular products and processes, and identify

major contributors to environmental impact. The Green Advisor team has identified existing green design tools that they will review, such as, ReStar from Carnegie Mellon University, Design for Service and Disassembly by Boothroyd and Dewhurst, Environmentally Responsible Product Design by Massachusetts Institute of Technology, Simapro by Pre, Ekologik by Chalmer Industriteknik, Hyper Green by Ohio State University, and Ecosys Life Cycle Information and Expert System developed by Sandia National Laboratory.

Young, Steven B. and Vanderburg, Willem H. "Applying Environmental Life-Cycle Analysis to Materials," *JOM*, April 1994, pp. 22-27.

The authors discuss the application of the life-cycle analysis method to materials. They distinguish between intrinsic and extrinsic material properties. Intrinsic properties are the conventional physical properties of a material (e.g., density, strength, conductivity) and extrinsic properties are "characterized by the history or circumstance of a product" (economic cost, environmental characteristics). In this article, three extrinsic properties are examined for steel, aluminum and polyethylene: gross energy requirement, global-warming

potential, and solid-waste burden. The use of alternative materials in an automobile component are examined using this method. This work is part of an on-going research project supported by the Ontario Centre for Materials Research.

C. REFERENCES FOR FURTHER RESEARCH

Ahmad, B.S. *A Literature Review of Life Cycle Assessment*, Technical Report, Department of Chemical Engineering, MIT, 77 Massachusetts Ave. Cambridge, MA 02139. June 1993, p. 28.

Allenby, B.A.. "Design for Environment: A Tool Whose Time Has Come," *SSA Journal*, September 1991, pp. 5-9.

Alting, L. "Life Cycle Design," *Concurrent Engineering*, Vol. 1, No. 6, Nov/Dec 1991, pp. 22-23.

Alting, L. "Life Cycle Design of Industrial Products: A New Challenge/Opportunity for Manufacturing Enterprises," *Proceedings, First Int. Congress on Environmentally Conscious Design and Manufacturing*, Boston, MA: The Management Roundtable, 1992.

Alting, Leo, & Jorgensen, Jorgen. "Life Cycle Concept as a Basis for Sustainable Industrial Production," *CIRP Annals*, Vol. 42, No. 1, 1993, pp. 163-167.

Association of German Engineers. *Design Technical Products for Ease of Recycling*, VDI2243, Germany, May 1991.

Ayres, Robert U. (Ed.) "Industrial Metabolism. In Ausubel and Sladovich," *Technology and Environment,* Washington, DC: National Academy Press, 1989, pp. 23-49.

Bailey, Paul E. "Life-Cycle Costing and Pollution Prevention," *Pollution Prevention Review*, Winter 1990/1991, pp. 27-39.

Beitz, W. *Design for Ease of Recycling*, Berlin: Technology University of Berlin, 1992.

Canadian Standards Association. *Environmental Life-Cycle Assessment, Part I—Life-Cycle Review/Concepts*, CAN/CSA-Z760.1, Toronto, Canada: Author, 1994.

Canadian Standards Association. *Environmental Life-Cycle Assessment*, CAN/CSA-Z760.2, Toronto, Canada: Author, 1994.

Clemson, Barry and Lowe, Ernest. "Total Quality Management and Comprehensive Change," *Engineering Management Journal*, March 1993, pp. 6-10.

Cohan, D., Wapman, K.R., McLearn, M. "Beyond Waste Minimization: Life Cycle Cost Management for Chemicals and Materials," *Pollution Prevention Review*, Summer 1992, .pp. 259-275.

Cohan, D. and Gess, D. "Managing Life-Cycle Costs," *Proceedings of The NAEP 18th Annual Conference: Current and Future Priorities for Environmental Management*, May 1993.

Curlee, T. Randall. *The Economic Feasibility of Recycling, A Case Study of Plastic Wastes*, New York: Greenwood Press Inc., 1984.

Duchin, Faye. "Industrial Input-Output Analysis: Implications for Industrial Ecology," *NAS Proceedings*, Washington, DC: National Academy of Sciences, 1992.

Ehrenfeld, John R. "Industrial Ecology: A Strategic Framework for Product Policy and Other Sustainable Practices," *The Second International Conference on Product Orient Policy*, Prepared for Green Goods, September 1994.

Fearncombe, John. "Designing for the 1990's Environment," *Proceedings of the Plastics Recycling Conference, 1993*, Brookfield, CT: Society of Plastics Engineers, 1993, pp. 153-160.

Gause, D.G., Weinberg, G.M. *Requirements: Quality Before Design*, New York: Dorset House, 1989.

Keoleian, G. A. "The Application of Life Cycle Assessment to Design," *Journal of Cleaner Production*, in press.

Lowe, Ernest. "Industrial Ecology: A Context for Design and Decision," *Design for Environment: Principles and Practices*, New York: McGraw-Hill, Inc., in press.

Navin-Chandra, D. "Design for Environmentability," DTM '91 American Society of Mechanical Engineers, Design Engineering Division DE v 31. ASME, New York, 1991, pp. 119-125.

Navin-Chandra, D. (Ed.). *Green Engineering: Designing Products for Environmental Compatibility*, in press.

Navin-Chandra, D. "ReStar a Design Tool for Environmental Recovery Analysis," *Proceeding of the International Conference on Engineering Design*, Hague, August 1993, in press.

Steen, B., Ryding, S. *The EPS Enviro-Accounting Method: An Application of Environmental Accounting Principles for Evaluation and Valuation of Environmental Impact in Product Design*, Stockholm, Sweden: Swedish Environmental Research Institute (IVL), 1992.

Tipnis, Vijay A. "Evolving Issues in Product Life Cycle Design," *CIRP Annals*, Vol. 42, No. 1, 1993, pp. 169-173.

U. S. EPA Science Advisory Committee. *Reducing Risk: Setting Priorities and Strategies for Environmental Protection*, Report SAB-EC-90-021 and 021A, Washington, DC: Author, 1990.

White, S. L., Becker, M. Savager, D. E. "Environmentally Smart Accounting: Using Total Cost Assessment To Advance Pollution Prevention," *Pollution Prevention Review*, Summer 1993, pp. 247-259.

APPENDIX A
GLOSSARY

Appendix A
GLOSSARY

CAE	computer-aided engineering
CSA	Canadian Standards Association
DFD	Design for Disassembly
DFE	Design for Environment
DFEQ	Design for Environmental Quality (Pitney Bowes)
DFMA	Design for Manufacture and Assembly
DFR	Design for Recycling
DFX	Design for X
DQA	data quality assessment
DQGs	Data quality goals
EDT	Environmental Design Team
EPA	Environmental Protection Agency
EPS	Swedish Environmental Priority Strategies
HEPI	Huber Environmental Performance Index (J.M. Huber Corporation)
ILCM	Integrated Life Cycle Model
ILES	Integrated Logistics Eco-Support
ILS	Integrated Logistics Support
JIT	Just in Time methods
LASC	Lockheed Aeronautical Systems Company
LCA	Life Cycle Assessment
LCCA	life cycle cost assessment model
LCIs	Life-Cycle Inventories
LCM	life-cycle cost integration model
LFWC	Lockheed Fort Worth Company
MDA-E	McDonnell Douglas Aerospace - East
NCMS	National Center for Manufacturing Science

OSHA	Occupational Safety and Health Administration
QFD	Quality Function Deployment
REPA	Resource and Environmental Profile Analysis
SETAC	Society of Environmental Toxicology and Chemistry
TCA	trichloroethane
TQEM	total quality environmental management). AT&T
TQM	Total Quality Management
TQRDC-E	technology, quality, responsiveness, delivery, cost and the environment

APPENDIX B
DISTRIBUTION LIST FOR IDA DOCUMENT D-1798

Appendix B
DISTRIBUTION LIST FOR IDA DOCUMENT D-1798

DEPARTMENT OF DEFENSE	No. of Copies
Deputy Under Secretary of Defense (Environmental Security) The Pentagon, Room 3E792 Washington, DC 20301 ATTN: Ms. Sherri W. Goodman	1
Principal Assistant Deputy Under Secretary of Defense (Environmental Security) The Pentagon, Room 3E792 Washington, DC 20301 ATTN: Mr. Gary D. Vest	1
Office of the Deputy Under Secretary of Defense (Environmental Security), Pollution Prevention 6 Skyline Place, 5109 Leesburg Pike Falls Church, VA 22041 ATTN: Ms. Carole Parker (EQ/PP)	1
Office of the Deputy Under Secretary of Defense (Environmental Security), Environmental Quality 400 Army Navy Drive, Suite 206 Arlington, VA 22202 ATTN: Mr. Peter Walsh, ADUSD (ES/EQ)	1
Ms. Maureen Sullivan (CO)	1
Office of the Under Secretary of Defense (Acquisition & Technology) The Pentagon, Room 3D139 Washington, DC 20301 ATTN: Lt. Col. Roy K. Salomon, Ph.D., P.E. (PP)	1
Office of the Deputy Under Secretary of Defense The Pentaton, Room 3D768 Washington, DC 20301 ATTN: Mr. Patrick Meehan, Jr.	1
Mr. Charlie Wood	5

OTHER ORGANIZATIONS	No. of Copies
Defense Technical Information Center (DTIC) 8725 John J. Kingman Road, STE 0944 Fort Belvoir, VA 22060-6218	2
Institute for Defense Analyses 1801 N. Beauregard Street Alexandria, VA 22311-1772	15
Total	**29**

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 1995	Final

4. TITLE AND SUBTITLE
Review of Literature on Environmentally Conscious Design

5. FUNDING NUMBERS
DASW01-94-C-0054
T-AM1-1290

6. AUTHOR(S)
Joyce C. Rigby

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Institute for Defense Analyses
1801 N. Beauregard Street
Alexandria, VA 22311

8. PERFORMING ORGANIZATION REPORT NUMBER
IDA Document D-1798

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Mr. Gary Vest
Office of the Deputy Under Secretary of Defense (Environmental Security)
The Pentagon, Room 3E792
Washington, DC 20301

FFRDC Programs
2001 N. Beauregard Street
Alexandria, VA 22311

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Public release/unlimited distribution; 12 April 1996.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

In support of current research tasks, IDA has reviewed the literature and prepared annotated abstracts of bibliographical information directly related to environmentally conscious design. This literature compilation focuses on industrial ecology, Design for Environment (DFE), and life cycle assessments. Additional topics include computer-based systems for environmentally conscious design, economic aspects of DFE, pollution-prevention activities centered on materail substitution or process change, risk analysis, and affirmative engineering, which addresses the recycling and economic reuse of previously used materials. Total quality management and system-oriented design are also included to the extent that they address environmental considerations.

14. SUBJECT TERMS
Design for Environment, environmentally conscious design/manufacturing, industrial ecology, pollution prevention in design/manufacturing, affirmative environmental activity, economic analysis of environmental designs, environmental design criteria

15. NUMBER OF PAGES
53

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	Same as report

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102